Increasing $h \to \gamma\gamma$

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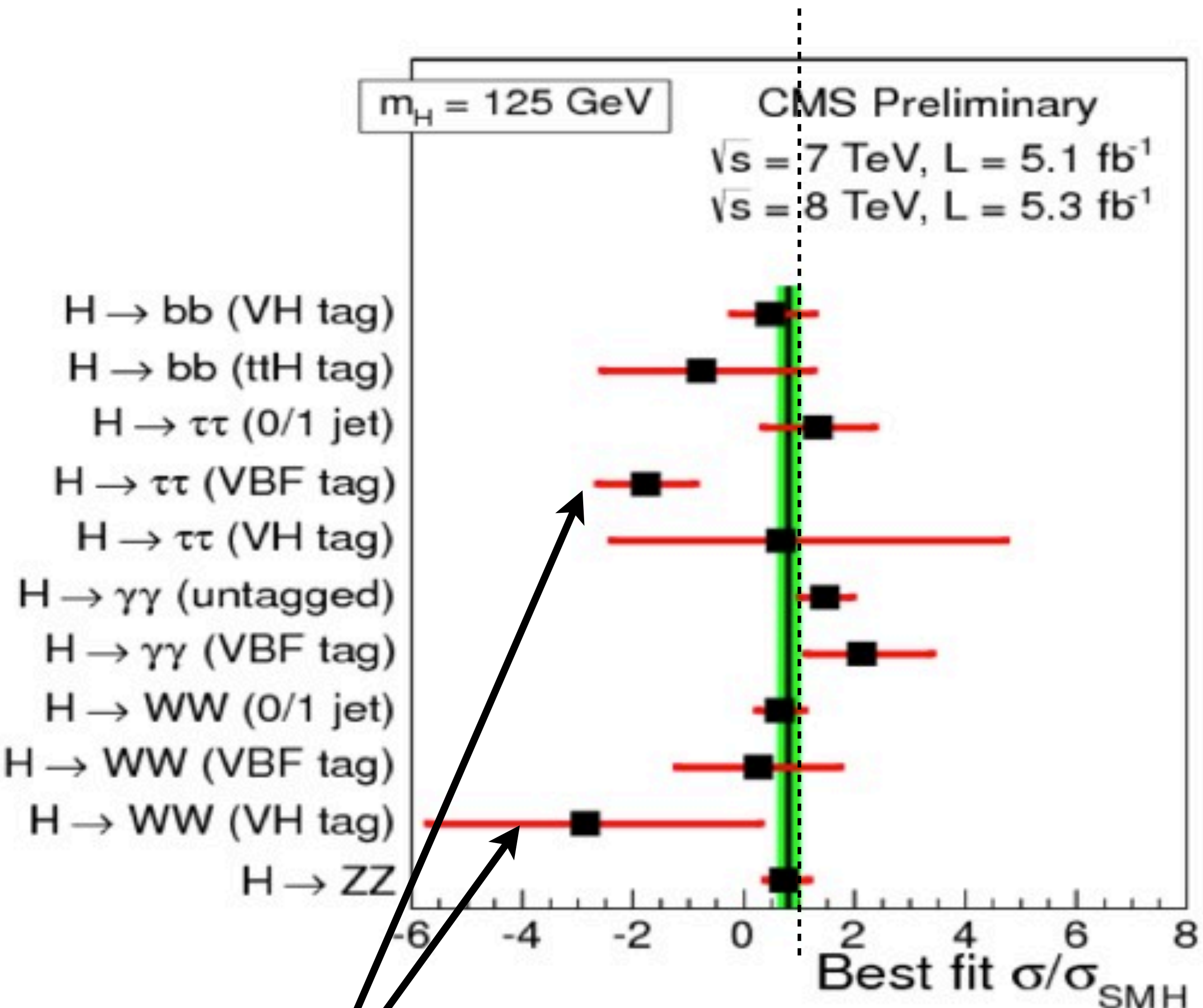
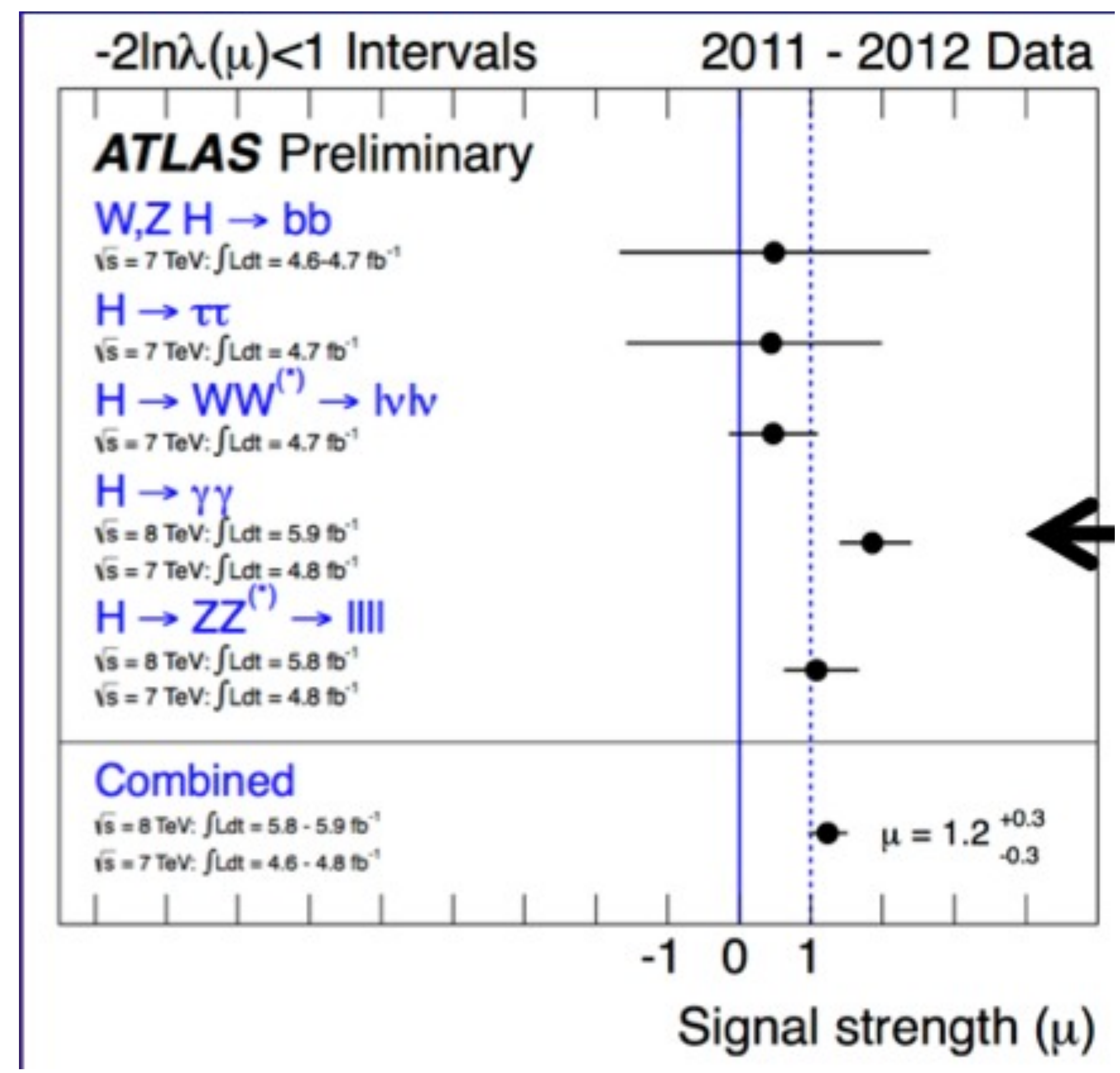
The Data





ignoring channels with likely downward fluctuations in background, CMS data within ~1σ of SM, γγ rate 1.56±0.43 x SM

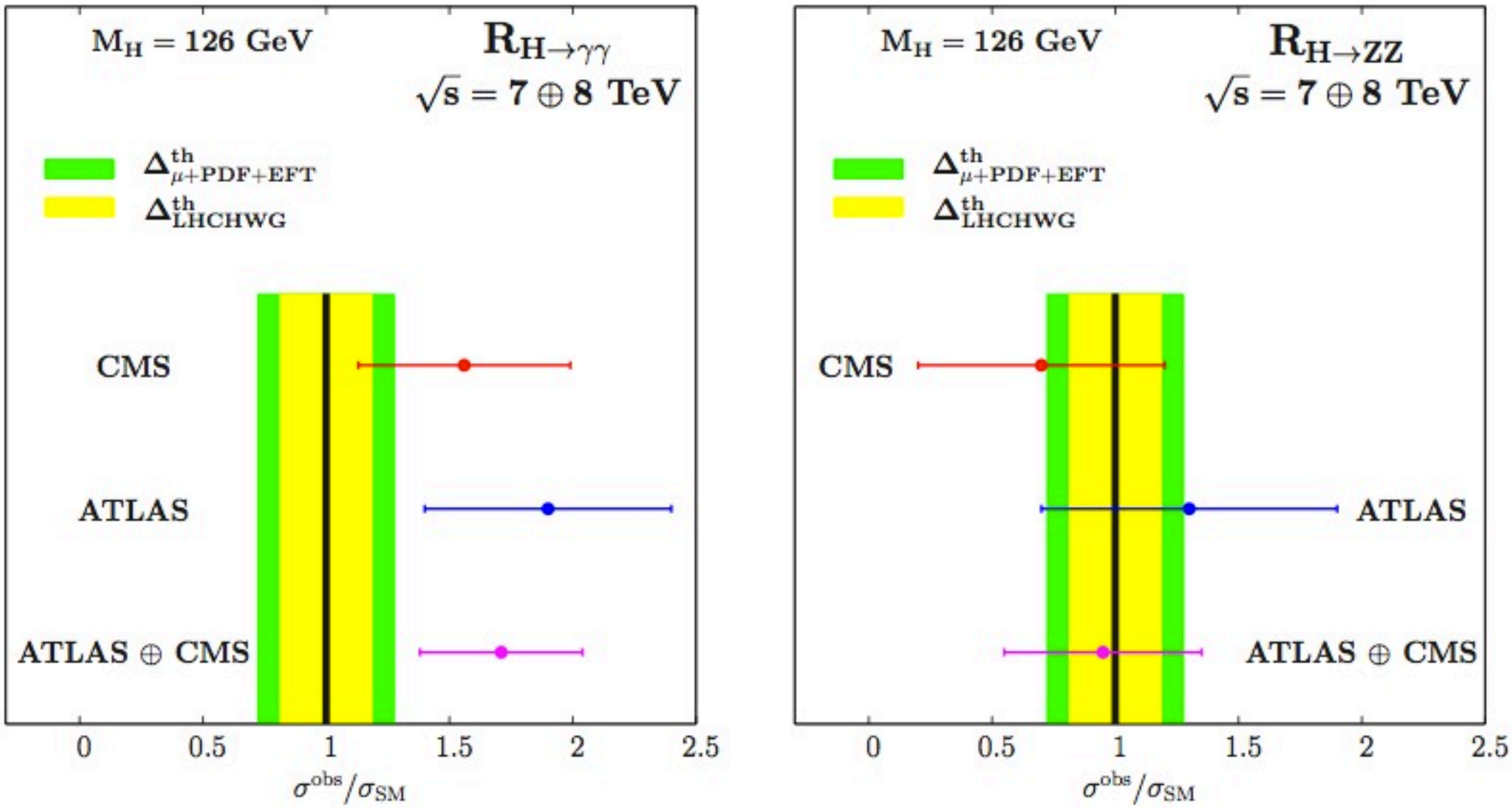
ATLAS ZZ* within 1σ of SM, γγ rate 1.9±0.5 x SM

Naive (uncorrelated, Gaussian) combination of γγ rates: 1.7±0.3 (Moriond: 2.1±0.5)

What is causing this enormous excess?

Theory Uncertainty?

Baglio, Djouadi, Godbole 2012



Adding theory errors linearly & treating as bias rather than nuisance can bring combined $\gamma\gamma$ fit to within 1.3σ of SM

Broadly speaking, most other proposals for increasing the inclusive $h \to \gamma\gamma$ rate use one/both of these mechanisms:

• New sources of EWSB modify SM couplings that appear in the rate:

-h coupling to W > $2m_W^2/(246\text{ GeV})$ (c/a effective models, Spencer's talk. also increases $h \to WW$, $Vh \to bb$)
-h coupling to b < $\text{Sqrt}(2)m_b/(246\text{ GeV})$ (decreases $h \to bb$, increases other rates)

• New states contribute to production and/or decay:

-increase $\sigma \times BR$ with new loops (stops with small mixing, staus with large mixing, W', vectorlike charged matter with negative coupling to Higgs portal, vectorlike colored matter with positive coupling to Higgs portal......)
-new final states that look like $\gamma\gamma$ (Brian's talk on degenerate Higgs families, $h \to aa \to$ 4 boosted γ)

The h++ model in Spencer's talk is an example that uses both mechanisms: direct increase of W coupling through new sources of EWSB, and h++ also appears in the $h \to \gamma\gamma$ decay loop

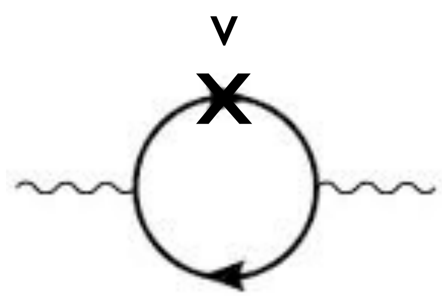
In this talk I'll focus on second mechanism (new particles in the production/decay); review examples of:

- mixed staus (Carena, Gori, Shah, Wagner 2011)
- $h \rightarrow aa \rightarrow 4\gamma$ (PD and D. McKeen 2012)

Reason for these examples: mainly influence the $h \rightarrow \gamma\gamma$ rate; everything else mostly SM-like

Modifying σ×BR with new particles X in loops

In the limit that $m_h << 2m_X$ and h is aligned with v,



Vacuum Polarization

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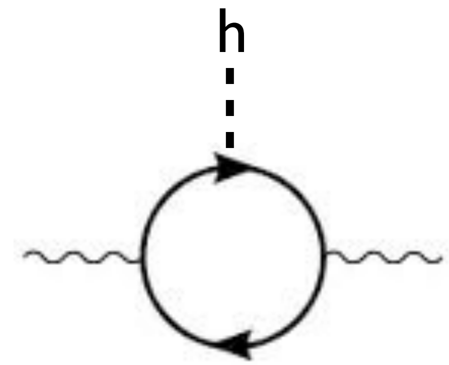
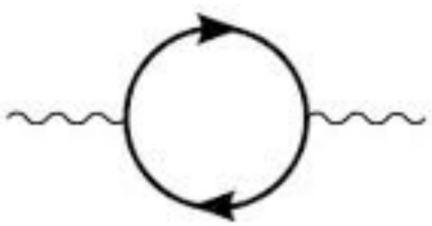
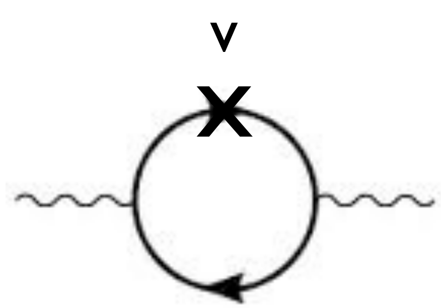


hFF effective coupling

× v



~$\Delta\beta \log m_X$, so



$$= \frac{\Delta\beta}{16\pi^2} \frac{\partial \log m_X^2(v)}{\partial \log v}$$

where $\Delta\beta$ is the shift in the EM or QCD beta function from integrating out X

from multiple X thresholds, get

$$\boxed{\frac{\Delta\beta}{16\pi^2} \frac{\partial \log \det \mathcal{M}_X^2(v)}{\partial \log v}}$$

for the effective hFF, hGG couplings

$$\frac{\Delta\beta}{16\pi^2}\frac{\partial \log \det \mathcal{M}_X^2(v)}{\partial \log v}$$

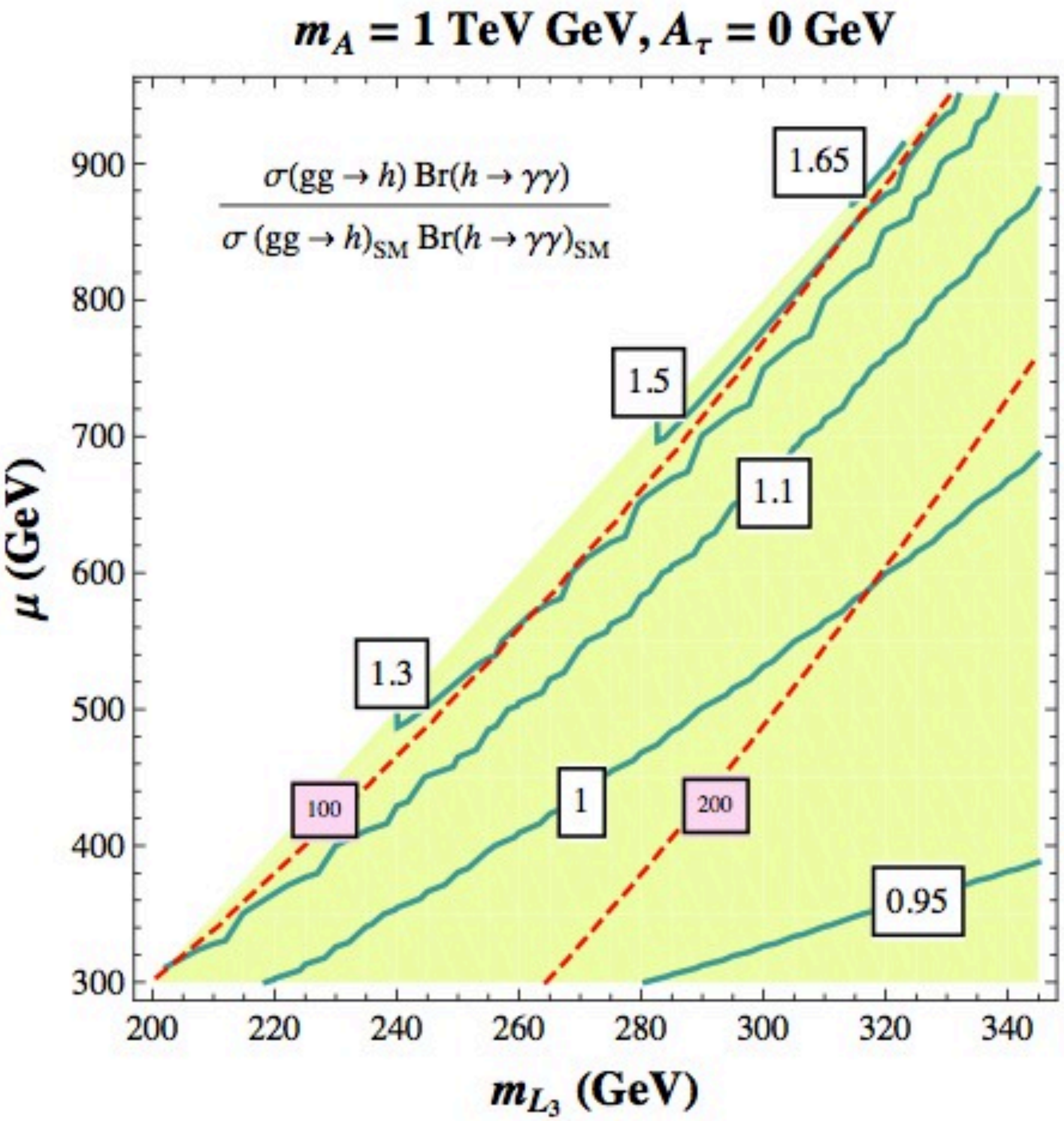
SM: top gives negative hGG coupling ($\Delta\beta<0$) and negative hFF coupling ($\Delta\beta<0$),
W gives larger positive contribution to hFF ($\Delta\beta>0$)

To enhance gluon fusion, easiest to have constructive interference with top loop, for example, stops with small mixing ($\Delta\beta<0$)

To enhance $\gamma\gamma$ width, easiest to have constructive interference with W loop
- -W' ($\Delta\beta>0$)
- -scalar or fermionic matter where off-diagonal contribution of v to M dominates and $\Delta\beta<0$

Staus with large mixing is an example of the latter:

$$\mathcal{M}_{\tilde{\tau}}^2 = \begin{pmatrix} m_{L_3}^2 + m_\tau^2 + D_L & m_\tau(A_\tau - \mu\tan\beta) \\ m_\tau(A_\tau - \mu\tan\beta) & m_{e_3}^2 + m_\tau^2 + D_R \end{pmatrix} \approx \begin{pmatrix} m_{L_3}^2 & -y_\tau^{SM}\tan\beta\, v\mu \\ -y_\tau^{SM}\tan\beta\, v\mu & m_{e_3}^2 \end{pmatrix}$$



Carena, Gori, Shah, Wagner, Wang 2012

need large mu*tan beta, stau just above LEP bound

A different possibility : new final states that look like γγ

Mechanism proposed by Dobrescu, Landsberg, Matchev (2001):

$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda^2}\left(\partial^\mu a\right)^2 H^\dagger H - \frac{e^2}{4M} a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

given m_h, have 3 basic parameters, which we take to be $\boxed{m_a,\ \ Br(h \to aa),\ \ M}$

- $\Gamma\left(h \to aa\right) = 1.18\ \mathrm{MeV}\left(\frac{m_h}{125\ \mathrm{GeV}}\right)^3\left(\frac{\Lambda}{\mathrm{TeV}}\right)^{-4}$ ⇒ Br(h→aa) easily non-negligible;
- Br(a→γγ) can be non-negligible for light enough pseudoscalars;
- $m_a/m_h \ll 1$ (PNGB) ⇒ photon pairs are highly boosted and can look like single γ;

⇒ 4γ final state becomes effective γγ contribution

Something different: new final states that look like $\gamma\gamma$

DLM studied @ the Tevatron. Can this be happening now at the LHC?

<u>Basic Requirements</u>:
"photon jets" need to pass stringent π^0 rejection (controlled by m_a)
satisfy Higgs rate @ LHC (controlled by m_a and $Br(h \to aa)$)
survive LEP search and low-energy constraints (controlled by m_a and M)
decays happen within detector radius (controlled by m_a and M)

We concluded:
- -viable parameter space exists
- -UV completions are baroque

PD and D. McKeen 2012

Modifications to SM Branching Ratios

$$\mathcal{B}(h \to \gamma\gamma)_{\text{eff}} = R_{\gamma\gamma} \times \mathcal{B}_{\text{SM}}(h \to \gamma\gamma),$$
$$\mathcal{B}(h \to f\bar{f}, VV) = R_{XX} \times \mathcal{B}_{\text{SM}}(h \to f\bar{f}, VV)$$

$R_{XX} = 1 - \mathcal{B}(h \to aa)$ (just from increasing total width)

Assuming 100% $a \to \gamma\gamma$,

$$\mathcal{B}(h \to \gamma\gamma)_{\text{eff}} = \mathcal{B}(h \to \gamma\gamma) + \epsilon \times \mathcal{B}(h \to aa)$$

ϵ is the probability that 4γ is misidentified as 2γ

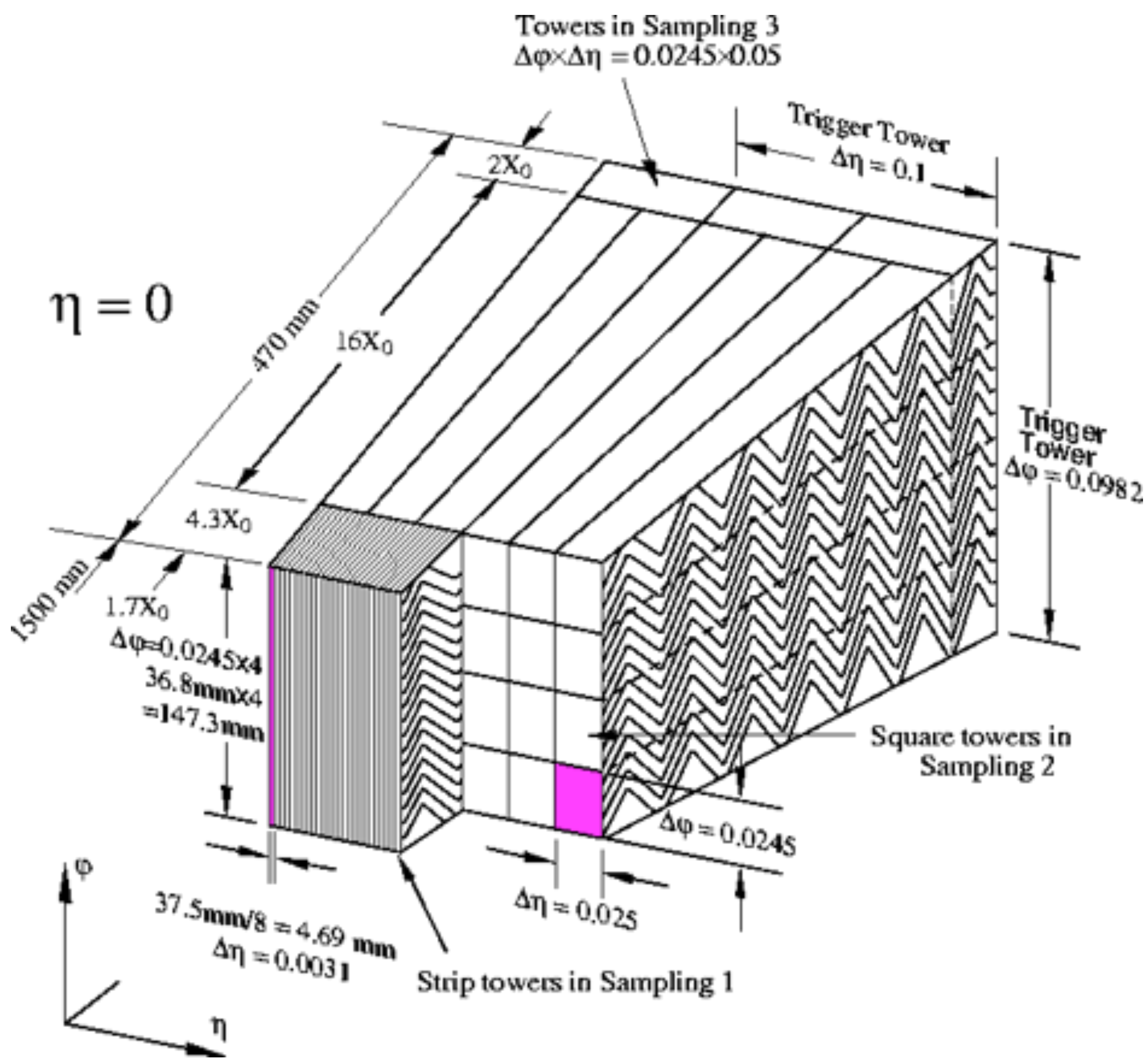
or

$$R_{\gamma\gamma} = 1 + \mathcal{B}(h \to aa)\left(\frac{\epsilon}{\mathcal{B}_{\text{SM}}(h \to \gamma\gamma)} - 1\right).$$

To get enhancement at m_h=125 GeV, $\epsilon \geq \mathcal{B}_{\text{SM}}(h \to \gamma\gamma) \simeq 0.0023$

Estimating ϵ

ATLAS efficiently vetoes isolated, boosted $\pi^0 \rightarrow \gamma\gamma$ using first ECAL layer, which has finely-segmented strips in rapidity



Most sensitive discriminator:

$$w_{s3} \equiv \sqrt{\sum_i E_i (i - i_{\max})^2 / \sum_i E_i}$$

On unconverted photons, ATLAS uses a weakly η-dependent cut on w_{s3}, approx 0.66 for the most central strips in the barrel.

Avg val for true photons approx w_{s3} =0.58

Estimating ϵ

We simulate $h \to aa \to 4\gamma$ events and attempt to mock up the more complicated cuts on ECAL variables with cuts on $\Delta\eta_{\gamma\gamma},\ \Delta\phi_{\gamma\gamma}$

Opening angles controlled by m_a

We find that requiring $\Delta\eta_{\gamma\gamma} < 1/2 \times \Delta\eta_{\rm strip}$ simulates the cut on w_{s3}. Also use $\Delta\phi < \Delta\phi_{\rm strip}$ although result is insensitive (much coarser in φ)

-Assume Gaussian profile for single photon energy deposit
-calibrate width to reproduce average true photon w_{s3}
-find $\Delta\eta$ for which two photons averaged over strip gives cut value for w_{s3}

Estimating ϵ

What about conversion events? Conversions happen with an η- and E_T-dependent probability ranging from about 10% at low η to more than 50% at larger η

Since we have twice as many photons, many more events contain at least one conversion

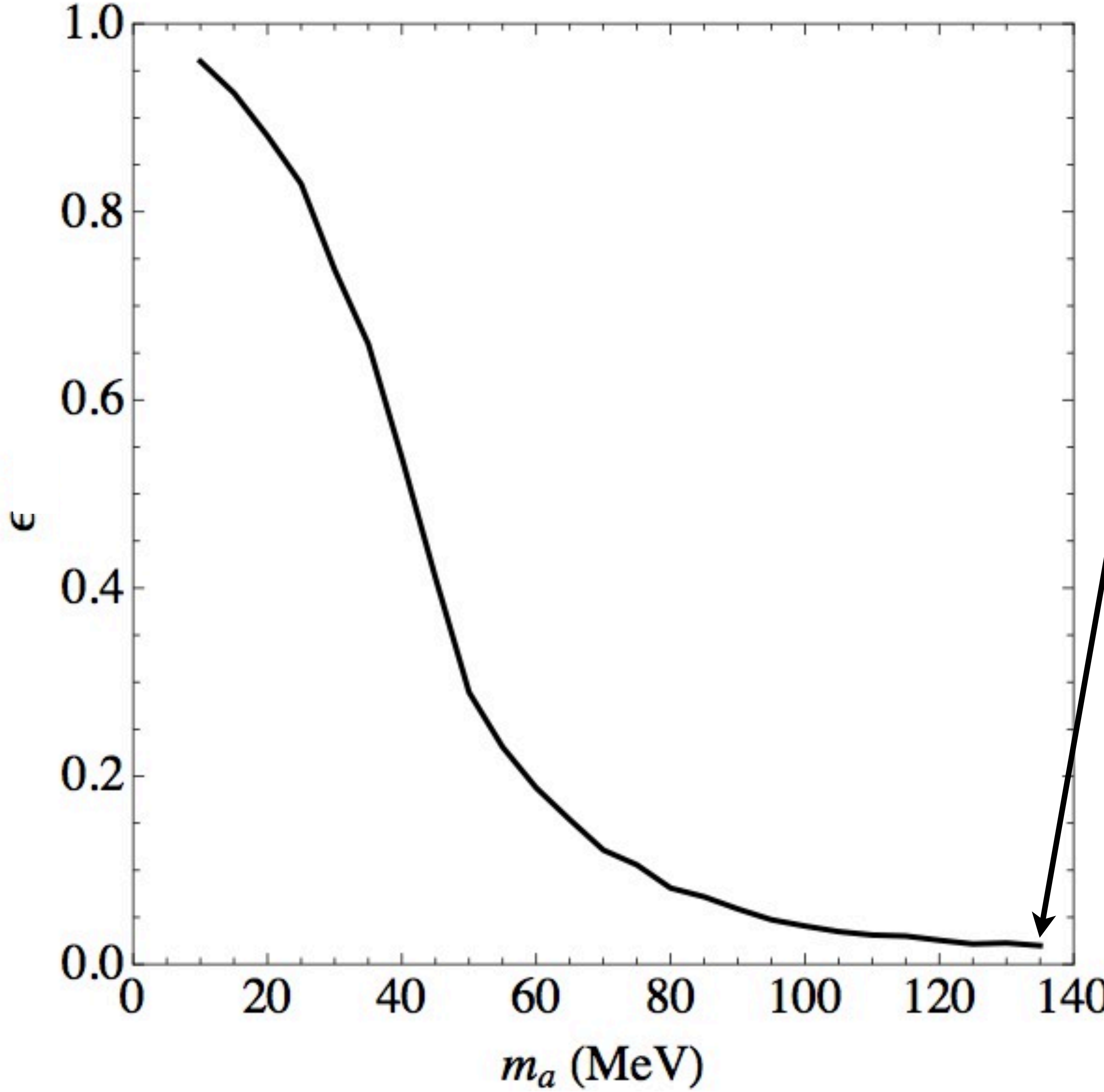
Might imagine these are vetoed:

- -for case with γe^+e^- in one cluster, mismatch between track p_T and energy in the calorimeter
- -for case with $2e^+e^-$ in one cluster, multiple conversion vertices

ATLAS currently does not veto on either, and relaxes cuts for conversion events since energy deposit spreads (a bit in η, and more in φ due to magnetic field)

We will make the approximation that the value of ϵ relevant for 4γ events containing conversions is the same as the value of ϵ for the unconverted sample, and validate for pion

Estimating ϵ



Matches expectation from known isolated π^0 rejection power on unconverted +converted sample

Substantial contamination requires m_a less than tens of MeV

CMS

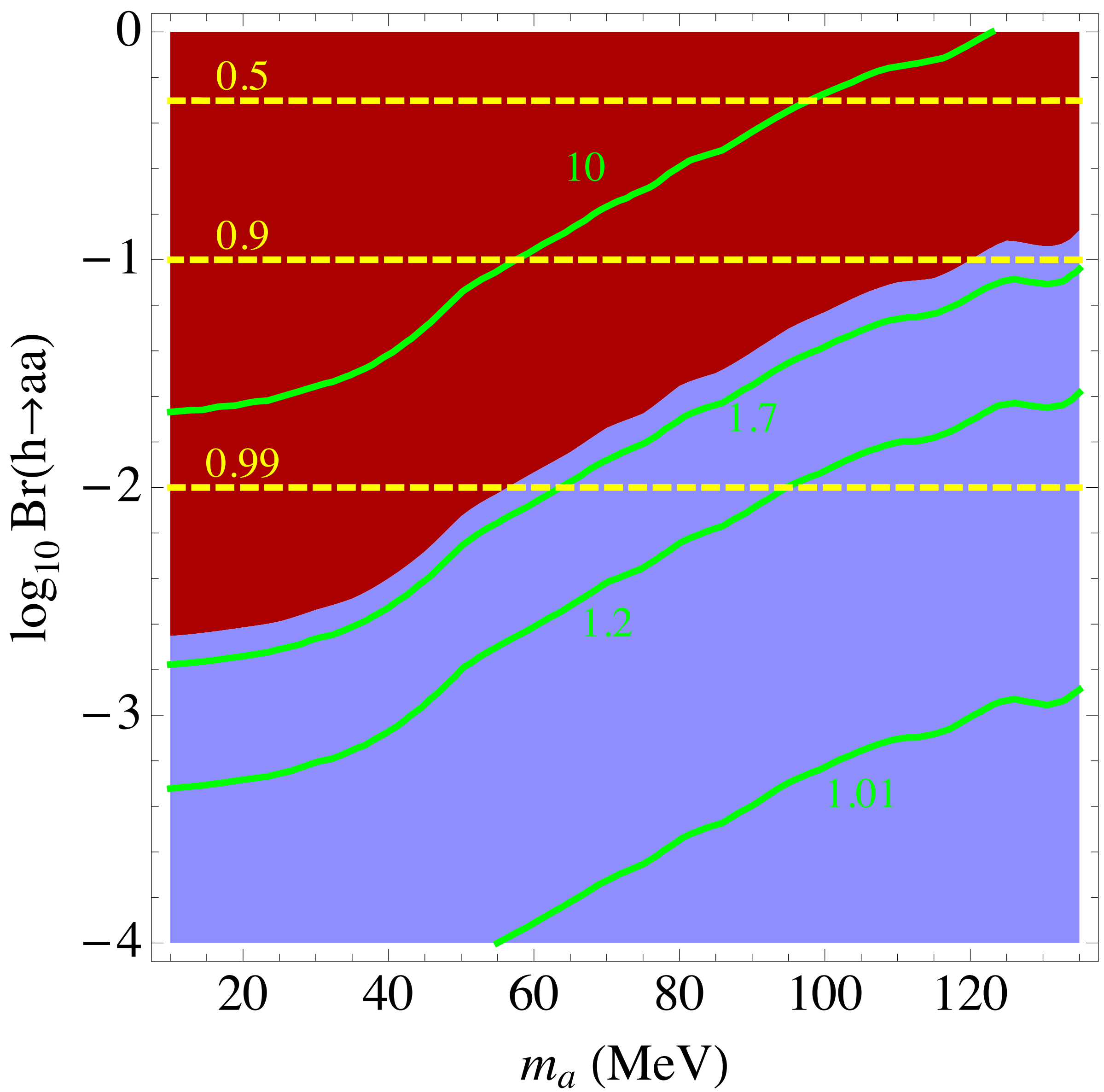
CMS does cut on the ratio of the calorimeter energy to the tracker p_T in order to isolate single photons

Also has 6x barrel strip size!

$\Rightarrow$ Expect a somewhat different ϵ between the two experiments

Predicted Rates at the LHC & Constraints

100% a→γγ



Contours give net diphoton (solid green) and ZZ,WW,bb,ττ rates (dashed yellow) expected at the LHC relative to the SM rates, using previous estimation for ϵ .

Constrain $(m_a, \mathcal{B}(h \to aa))$ parameter space with matched filter

$$\hat{R} = \sigma^2 t_i C_{ij}^{-1} d_j$$
$$\sigma \equiv (t_i C_{ij}^{-1} t_j)^{-1/2}$$

Compute $\hat{R}$ at each point, reject if R=1 is outside 90% CL

Favored points lie along green 1.7 contour; χ^2 shallow along contour, so:

any m_a ok,

Br(h→aa) between 0.1% and a few %.

Direct Constraints

Constrain m_a, and M through $\frac{e^2}{4M} a\, F^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling

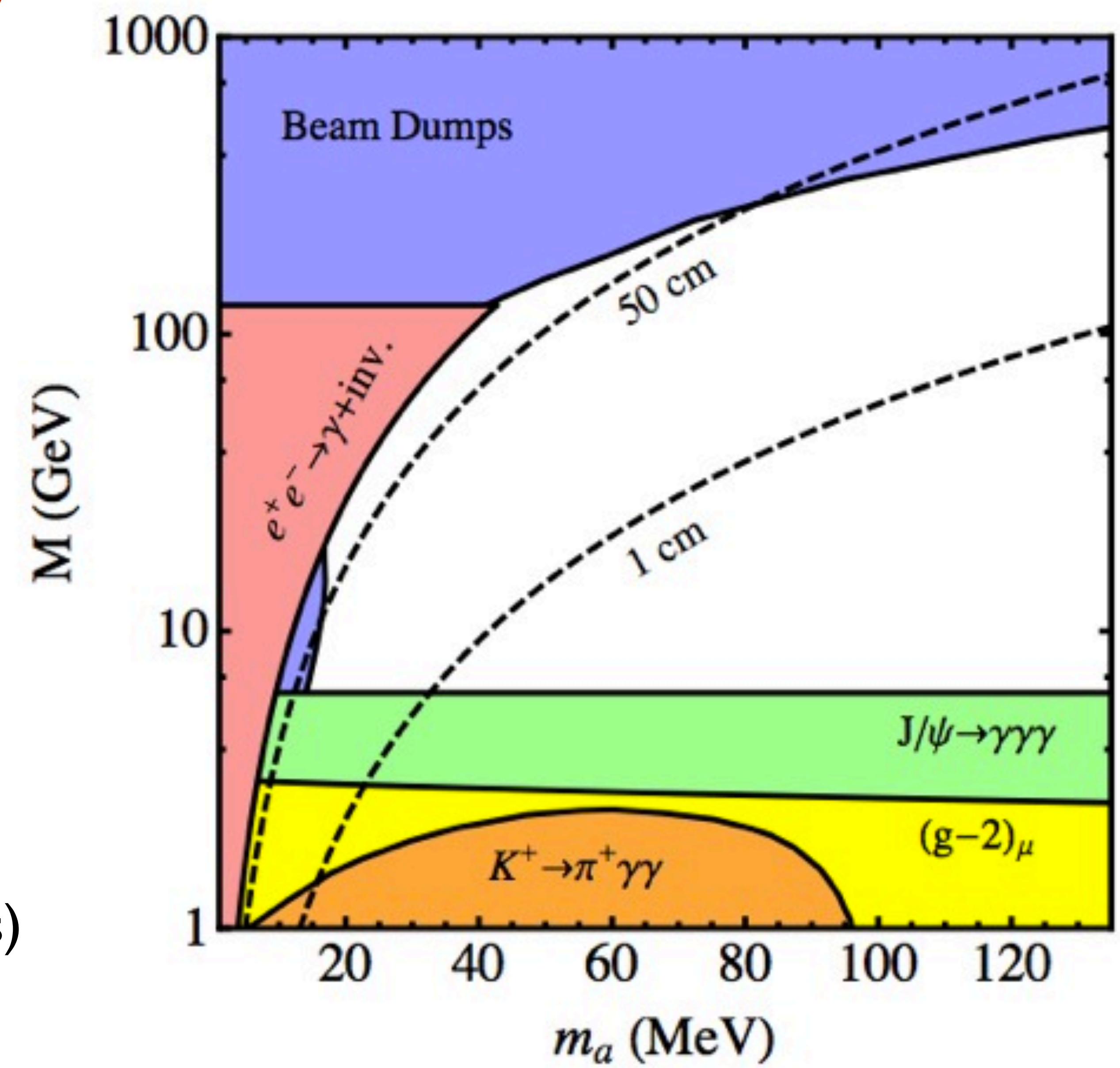
Constraints from Primakoff production in beam dump experiments: ok so long as a's decay length is shorter than the target depth, or past detector

Similarly LEP search for $e^+e^- \rightarrow \gamma$+inv ok if a decays before the detector

These bounds coincide roughly with requirement that decay happens before detector at LHC

quarkonia can decay to γa through an s-channel virtual photon $\Rightarrow$ lower bound on M

other constraints (g-2, flavor-violating meson decays) more sensitive to additional couplings of pseudoscalar to SM fermions



Model Building Issues for $a\,F^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling

- Decay length constraints require large $a\,F^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling. For a given decay length,

$$M = 9.3 \text{ GeV} \left(\frac{\gamma c\tau}{1 \text{ cm}}\right)^{1/2}\left(\frac{m_a}{40 \text{ MeV}}\right)^2 \times \left(\frac{m_h}{125 \text{ GeV}}\right)^{-1/2}$$

To get 90% of the decays before the ECAL (~1m), need < 1/2m decay length, so M less than about 200 GeV.
If M generated by integrating out heavy particles, $M \sim 4\pi^2 m/q^2$
So those particles have masses below 10s of GeV: must be SM fermions unless high multiplicity or large q

- NMSSM a possibility. However, light a in NMSSM totally ruled out in this mass range by multiple low-energy measurements Andreas, Lebedev, Ramos-Sanchez, & Ringwald 2010

- Could work if light a couples only to the tau lepton.
  $(g-2)_\tau$ poorly known, only constrains M>35 GeV.

Conclusions

In case $h\to\gamma\gamma$ > SM persists, interesting to delineate possible mechanisms

Minimal SUSY ⇒ small-α scenario or light staus in decay loop; many other possibilities in the loop beyond minimal SUSY.

$h\to aa\to 4\gamma$ with γs collected into two photon jets is another possibility

- Favors pseudoscalars between 10 MeV and pion mass and percent-level branching of $h\to aa$
- Low scale of physics generating the $a\,F^{\mu\nu}\tilde{F}_{\mu\nu}$ coupling suggests SM particles; constraints on these couplings make UV model building tricky

Backup

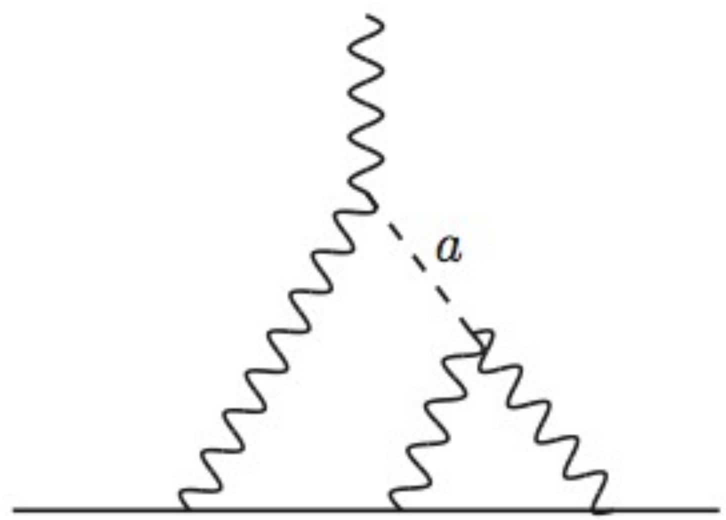


FIG. 3. A representative diagram of the leading contribution of the pseudoscalar, a, to $(g-2)_\mu$.

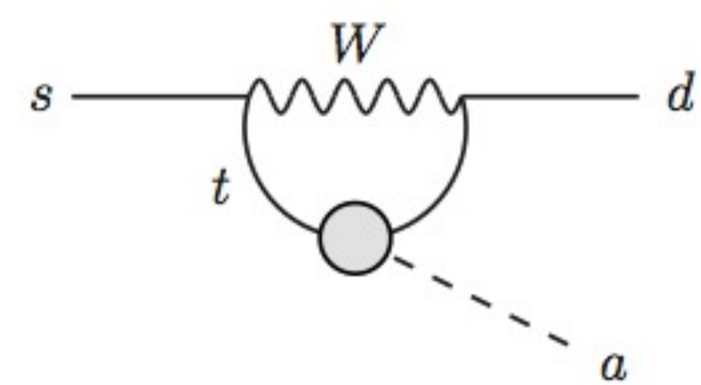


FIG. 4. Diagram that gives the leading contribution to $s \to d + a$ from an effective interaction between a and the top quark.